MOTION ADAPTIVE 3D Y/C SEPARATION ALGORITHM USING MOTION ESTIMATION AND MOTION COMPENSATION

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Abstract
This paper proposes an advanced motion adaptive three-dimensional (3-D) Y/C separation algorithm for NTSC signals. The basic principle of Y/C separation processing uses the fact that the phase information in a composite signal inverses every horizontal pixel, vertical line, and temporal field/frame. As such, this phase inversion characteristic is used to separate the Y and C components from a composite signal through an addition and subtraction operation. However, inaccurate separation introduces deterioration in quality, such as cross color and cross luminance, due to lack of regard for motion information. Accordingly, to acquire accurate movement information, the proposed algorithm uses a 2-D separated Y signal for detecting moving regions and estimates a motion vector using BMA-based motion estimation. Thereafter, the Y and C components are separated using the phase inversion characteristic and motion compensation (MC). Experimental results demonstrated a significant reduction in cross color and cross luminance in moving pattern regions.

Keywords: Y/C separation, motion-adaptive, motion estimation, motion compensation

1. INTRODUCTION

Currently, a lot of attention is being paid to high-definition television (HDTV) along with extended-definition TV (EDTV) and improved-definition TV (IDTV). EDTV improves the TV picture quality by modifying the NTSC standard while maintaining a compatibility with the existing signals. In contrast, IDTV requires no modification of the NTSC signal itself, yet aims to make the best of the transmitted signal by improving the incompleteness of the TV receivers. Recent theoretical advances in multidimensional signal processing have made it possible to both interpret and process NTSC signals three-dimensionally. Yet, this 3-D interpretation has clarified several causes that degrade the existing TV picture quality. For example, problems related to line-interlaced scanning and incomplete luminance/chrominance separation are most commonly discussed in previous literature, e.g., [1], [2], and [3]. The former originates in aliasing line-interlaced scanning without prefiltering and can be avoided to some extent by introducing a scanning line decimator/interpolator [6]. The latter problem is the subject of the present study. In NTSC signals, it is well know that chrominance (C) signals are interleaved into luminance (Y) signals to make composite signals, which are then transmitted using a single channel. However, in order to process and display such composite signals, the C signals have to be separated first. As shown in Section 2, Y and C signals are currently insufficiently separated by 1-D and 2-D filters in existing TV systems. Such insufficient separation introduces picture impairments known as cross color or cross luminance. Recently, these impairments, especially cross color, have become more noticeable due to the development of high-quality TV cameras where the luminance signals contain higher frequency components than earlier TV cameras.

Although a complete separation of interlaced Y and C signals is actually impossible with any kind of filter, since the lack of pre-filtering due to band limitations causes the Y and C signals to be overlapped in NTSC encoders [7] and [8], a better separation performance is expected with a 3-D Y/C separation filter because TV signals have a spatio-temporal 3-D nature. The 3-D filtering of moving pictures requires an extensive memory capacity and high-speed signal processing, neither of which was available until the appearance of VLSI. Accordingly, the rapid development of current VLSI technology has made it possible to realize video-rate multidimensional filters and frame/field memories on a single chip at a low cost, along with the possibility of 3-D TV signal processing.

This paper presents the design and implementation of 3-D Y/C separation filtering. As shown in section 2, several 3-D Y/C separation filters have been already

Contributed Paper
Manuscript received July 16, 2001
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proposed [2], [3], [7], and [8]. However, none of these filters can produce a high quality result in a moving region, which has a significant effect on the edge recovery performance. The 3-D Y/C separation method proposed in the current study emphasizes the treatment of a moving region and considers the adaptation of algorithms used for digital image processing.

This paper is organized as follows: section 2 reviews NTSC signals and encoding system, plus existing Y/C separation filters. Section 3, outlines the necessity of motion estimation and introduces the proposed motion adaptive Y/C separation method. Section 4 presents the experimental results.

2. Y/C SEPARATION OF NTSC SIGNALS

2.1. NTSC Signal

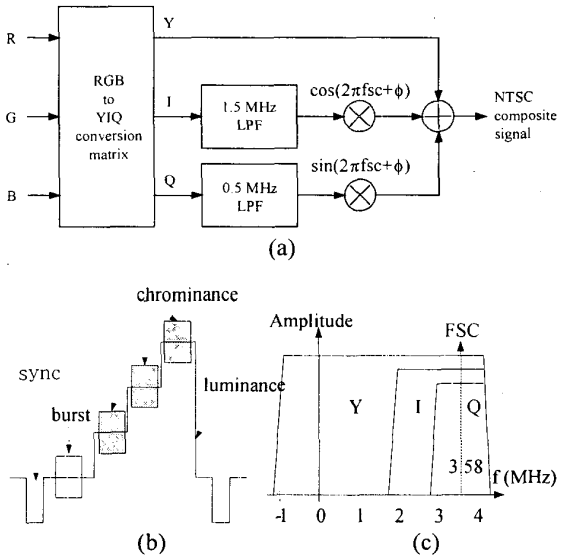

Fig. 1. Standard NTSC encoding system and signals. (a)Encoding system. (b) Time domain distribution. (c) Frequency domain distribution.

Fig. 1 depicts a standard encoding and decoding system for NTSC signals along with its signal level and typical frequency spectrum. To accommodate the requirement of a single-channel transmission, the Y and C (I and Q) signals are multiplexed, thereby leading to the well-known frequency interleaving structure. As shown in Figs. 1(b) and (c), the chrominance signals are added to the level of the luminance signals in the time domain and then interleaved with the luminance centered at 3.58 MHz in the frequency domain. Then, at the receiving set, the Y and C components of the composite signal need to be separated to regain the original red-green-blue signals. Insufficient separation introduces undesired cross color, cross luminance, and so on. As such, the performance of the separation circuit exerts a significant impact on the visual quality of the resulting TV pictures.

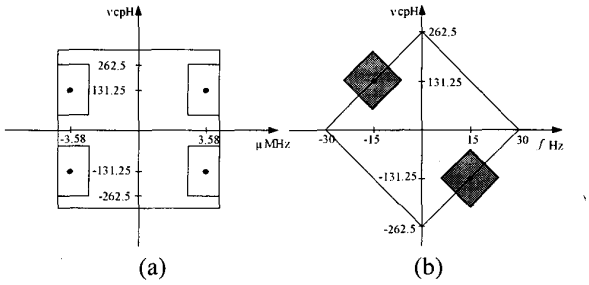

Fig. 2. 3-D structure of NTSC signals. (a) Horizontal-vertical plane. (b) Temporal-vertical plane.

NTSC signals have already been discretized in the vertical and temporal direction by scanning, whereas they are continuous in the horizontal direction, thereby requiring the signals to be sampled in an appropriate way to obtain fully digital NTSC signals. Although various 3-D sampling schemes have already been proposed, this paper assumes the simplest method of sampling a NTSC signal, i.e., orthogonal sampling on the horizontal-vertical plane with the sampling frequency $4f_{sc}$=14.3 MHz [5], where f_{sc} is the color subcarrier frequency (3.58 MHz).

Because moving pictures are three dimensional in nature, the 1-D spectrum of a composite TV signal can be best interpreted as a 3-D spectrum, which makes the treatment of the TV signal quite simple. The 3-D spectral structure of an NTSC signal is shown in Fig. 2 [4], [5].

As shown in Fig. 2, the color subcarrier fsc is located at four of the eight corners in the 3-D spatio-temporal frequency domain, while the C signal is located close the position of the subcarrier as a sideband. However, it should be noted that in the μ-ν frequency plane the existing area of the C signal is not strictly prescribed in the NTSC standard.

2.2. Y/C Separation

Based on a 3-D interpretation of NTSC signals it is understood that multidimensional filtering is required to properly separate the C components from the composite signal. Generally, Y/C separators can be classified into three groups based on the dimensions of the filter [1], [4]. The simplest Y/C separator is a 1-D BPF that corresponds to 1-D processing using the horizontal axis, as shown in Fig. 3(a). Although this type of separator is widely used in standard color TV sets due to the simplicity of its circuit, C signals from about 3 MHz up to 4 MHz are extracted together with the Y signal, thereby resulting in serious cross coloring.

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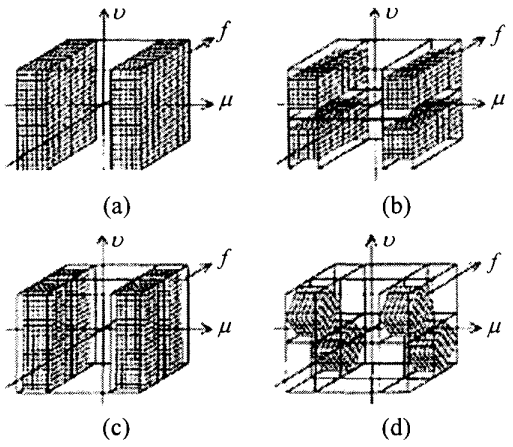

Fig. 3. 3-D structure of Y/C separation filters. (a) 1-D filter. (b) Line comb filter (c) frame comb filter (d) 3-D comb filter.

A superior separating performance can be achieved using 2-D Y/C separators that utilize comb filters including a number of line delays (1H-delays) [9]. Figs. 3(b) and (c) illustrate examples of the areas that 2-D separators extract as the C component. Fig. 3(b) corresponds to interline processing and is suitable for vertically pin-striped pictures, whereas Fig. 3(c) shows interframe processing, which, although not as widely used as interline processing, works best for stationary pictures. While a 2-D Y/C separator can reduce cross coloring to a certain extent in comparison with 1-D processing, the separation performance never reaches the limit of the NTSC system.

The recent rapid developments in low-cost digital memories have also brought the introduction of 3-D TV signal processing, including 3-D Y/C separation. 3-D processing facilitates a better separation of Y and C components as shown, for example, in Fig. 3(d). A motion-adaptive 3-D Y/C separation filter has already been proposed and applied in certain high-quality TV receivers [2], [3]. This filter adds the outputs of the 2-D separators in Figs. 3(b) and (c) adaptively to obtain C signals in accordance with a movement coefficient calculated by a motion detector. Even so, the motion adaptation in this system is still insufficient because it is only controlled by one parameter, i.e., the low-frequency components of the temporal frequency, thereby discarding any vertical information. Furthermore, on the temporal-vertical frequency plane, diagonal components extracted as C signals can be found in the second and fourth quadrants as well as in the first and third quadrants, which causes cross coloring for pictures moving in a certain direction.

2.3. Conventional Y/C Separation algorithms

The principle of Y/C separation is the phase inversion of a composite signal. Based on this characteristic a 3-line comb filter uses two lines located above and below a reference line, respectively. Fig. 4 shows a sample composite signal where s_2, s_4, and s_8 represent the upper neighbored, reference, and lower neighbored lines, respectively. The C component is separated by subtracting the upper and lower lines from the doubled reference line value, then dividing this by four as follows:

$$C_5 = (-s_2 + 2s_4 - s_8)/4 = \{-(Y-I) + 2(Y+I) - (Y-I)\}/4 = I \quad (1)$$

This filter exhibits a good performance when the three lines used in operation are similar to the Y and C distribution, that is, vertically stationary regions are appropriate for separating the C signal when using a two-dimensional comb filter. However, if a horizontal boundary exists among the operating lines, a 3-line comb will not produce a sharp edge due to the dissimilar signal distribution.

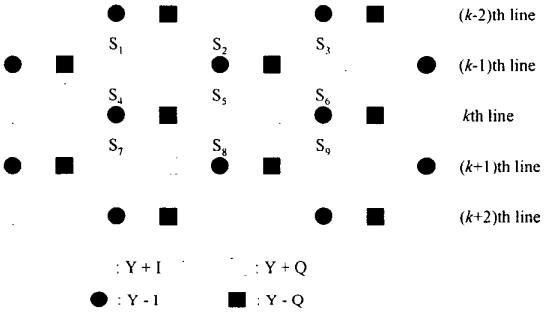

Fig. 4. Distribution of sample composite signal.

In the case of an edge including a horizontal boundary, if the object in the picture is temporarily still, the frame comb filter carrying out the addition and subtraction between the previous frame and the current frame can perfectly separate the Y/C signals due to the similar signal distribution. The mathematical expression of the frame comb filter, referred to as a three-dimensional Y/C separator, is shown below:

$$C_t = (-s_{t-1} + s_t)/2 = \{-(Y-I) + (Y+I)\}/2 = I \quad (2)$$

Although this filter can almost perfectly separate Y/C signals, it still has serious problems with moving pictures. To overcome cross color and cross luminance in a moving region, the first consideration is to determine whether or not a region contains motion.

Accordingly, a motion-adaptive three-dimensional comb filter performs the initial movement detection procedure, which decides whether a region as still or

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moving. Then for a still region, a frame comb filter performs the Y/C separation, while for a moving region a 3-line comb filter does the job. Conceptually, this filter operates similar to a 2×1 MUX, which uses the outputs of a 3-line comb filter and frame comb filter as two data inputs and the output of a movement detector as the selection input. The Y/C separated results show an improved quality for a moving region, yet still do not overrun the capability limit of a 3-line comb filter and frame comb filter.

In particular, the separation output depends heavily on the performance of the movement detector. In a conventional motion-adaptive comb filter [10], [11], the movement detector simply calculates the mean squared or absolute different value of the composite signal and then checks whether or not the value is greater than a given threshold. In contrast, to separate Y/C accurately in a moving region, the motion detector has to identify a block with a similar signal distribution and utilize a motion vector that points the degree of movement.

3. PROPOSED MOTION ADAPTIVE 3-D Y/C SEPARATION

3.1. Problem Definition

Conventional Y/C separation methods result in cross color and cross luminance in those regions where there is a different signal distribution due to movement. This particularly effects the overall quality of edges, which are especially sensitive points for human vision. These errors resulting from movement can be reduced by motion estimation (ME) as used in digital image processing. However, the composite signal in an NTSC TV system has a different image format from a digital image sequence, as such, a motion estimation algorithm can not be applied to TV signal processing.

An NTSC composite signal consists of luminance (Y) and chrominance (I and Q) components with phase characteristics, whereas a digital image sequence consists of R, G, and B components. In a digital image, if two adjacent pixels belong to the same object, each R, G, and B value will be very similar. Yet, under the same conditions, this is not the case with a composite signal due to the phase influence on the level of the analog composite signal. Therefore, a signal with similar characteristics within the digital image sequence needs to be identified in order to apply a motion estimation algorithm to Y/C separation processing.

As shown in Fig. 5, the sample composite signal has a different phase per pixel, yet the same pattern with a uniform spatial interval. Based on this pattern, the proposed method processes the Y/C separating operation using a block with the same pattern. This block-based processing compensates for any external noise, such as spike noise, and reduces the computation burden, whereas pixel-based processing is sensitive to noise and can not cope with the phase problem. However, the selection of the block size is important. If the size is too large, this increases the size of the errors due to the assumption that pixels in the same block include the same information.

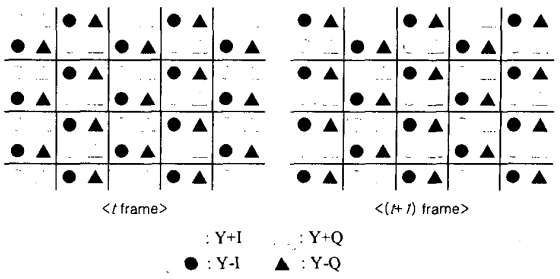

Fig. 5. Characteristics of composite signal with uniform pattern.

Generally, in an operation related to motion block-based algorithms, the output has a distorted quality due to the blocking artifact and exhibits saw tooth-shaped boundaries. The proposed method uses a 2x2 size as the dimension of the operating block in order to overcome the sensitivity related to the pixel-based method and the blocking artifact related to the large block-based method. Fig. 6 shows a comparison between a pixel-based, 2x2 block-based, and 4x4 block-based operations. The real moving regions in the test image were a women's body and waves. Fig. 6(b) shows the most accurate result.

3.2. Movement Detection

A scene is classified into different types of regions according to the movement. Each Y/C separation filter outputs a different result according to the characteristics of the input scene. If the scene is still or temporarily static, a frame comb filter exceeds the ability of a line comb filter. In contrast, if the scene includes a large movement, for example a camera tilt, a line comb filter produces a better result. Accordingly, these alternatives are resolved by dividing the scene into moving and static regions.

A moving region can be detected by calculating the similarity between a 2x2 block in the t-1 frame and t frame. However, the choice of the calculation measure affects the performance of the moving region detection. If a composite signal is selected, moving regions can be incorrectly detected owing to the effect of the phase on a composite signal. Fig. 7 shows an example of sequential frames containing pixels that have the same Y, I, and Q values located in the same positions, respectively. In contrast, composite signal values in sequential frames are

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not the same because the phase in the chrominance component is inverted every frame. As such, since the block difference value is not zero, and results in incorrect moving region detection.

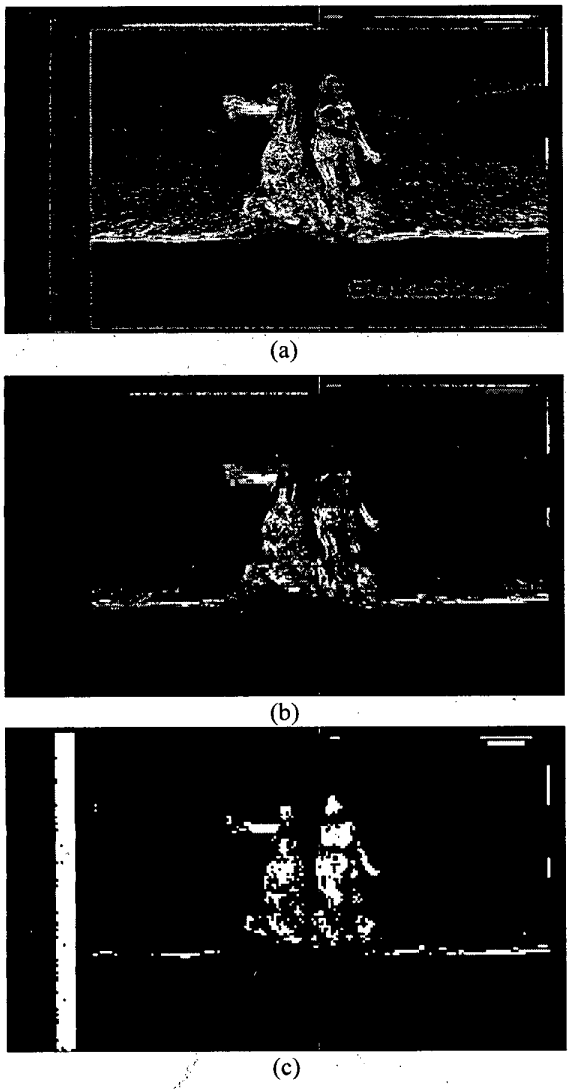

Fig. 6. Results of movement detection with different block sizes. (a) pixel size. (b) 2x2 size. (c) 4x4 size.

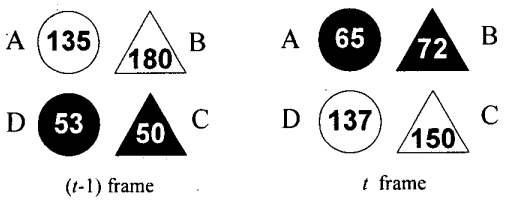

Fig. 7. Example of pixels with same value, yet different composite values.

The use of a block difference value as a measure for movement detection in conventional algorithms assumes that the distribution of the signal is continuous, i.e. has a similar value. Accordingly, to guarantee this assumption, this paper uses the luminance signal through a line comb filter as the measure for moving region detection as follows:

$$moving_region[a][b] = \begin{cases} 0, & \sum_{i=0}^{1}\sum_{j=0}^{1} |Comp_{t-1}[a+i][b+j] - Comp_t[a+i][b+j]| < T_{md} \\ 1, & otherwise \end{cases} \quad (3)$$

Line comb filtering involves a low computational burden and any errors from the line comb filter can be ignored since they have a minimal effect on detecting an over-valued block difference. As shown in Eq. (3), a moving region is detected if a block has a larger block difference value than a given threshold. In Eq. (3), a and b, Y, and Tmd represent the current block position, luminance signal from the line comb filter, and threshold value obtained heuristically, respectively The threshold value was set at 60.

3.3. Motion Vector Estimation

To extract a moving region, the proposed method adopts the block-matching algorithm (BMA) frequently used in motion estimation [12]. The BMA identifies the block most correlated with a reference block from among candidate blocks within a search range. Fig. 8 shows the BMA searching for the most similar block through raster scanning.

Since the proposed method operates 2x2 block-based processing, the reference block moves per two pixels in both the horizontal and vertical direction. Motion estimation using the BMA can be represented as follows:

$$(p_m, q_m) = \min\left(\sum_{i=-m}^{m}\sum_{j=-m}^{m} |Y_t(a+i,b+j) - Y_{t-1}(a+p+i,b+q+j)|\right), \quad (4)$$
$$for \quad p_{\min} < p < p_{\max},\ q_{\min} < q < q_{\max}$$

where (p_m, q_m), (a,b), (p,q), $(p_{\min}, q_{\min})$, and $(p_{\max}, q_{\max})$ represent the estimated motion vector, position of the reference block, candidate vector, and lower and upper bound of the candidate vectors, respectively.

If an instantaneous velocity runs over the search range, the object is non-rigid, or the region of the search range is static distribution, then the estimated vector will have a low reliability. Therefore, the proposed method has to perform the thresholding procedure based on the

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minimum block difference to check the reliability of the estimated vector. In the case of a static region, since the difference between block difference values is small, the vector with the minimum block difference is determined by means of external noise rather than similarity. This region can be found mathematically by calculating the variance in the block difference within the search range.

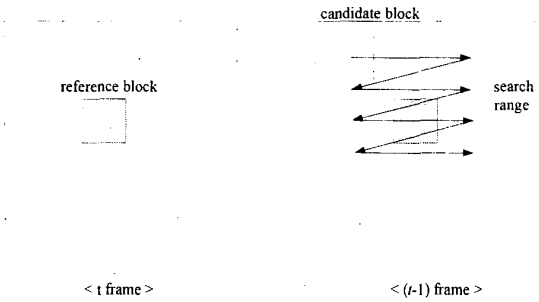

Fig. 8. Operation of block matching algorithm.

Fig. 9 shows a flowchart for checking the estimated motion vector. The output values LOGIC_0 and LOGIC_1 represent an unreliable and reliable sign, respectively.

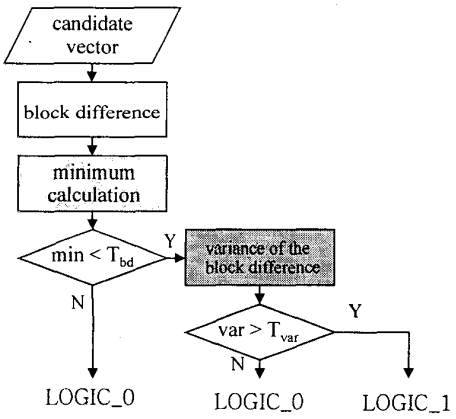

Fig. 9. Flowchart for reliability checking.

3.4. Motion Compensation-based Y/C Separation

The basic principle of Y/C separation uses phase inversion under the assumption that the processing lines have a similar signal distribution. However, the proposed method, which performs a 2x2 block-based operation, can deal with the situation where the phase inversion characteristic can not be used. As shown in Fig. 10, in the case of two pixels with a reversed phase, the Y/C can be easily separated, whereas this is not the case with two pixels with an identical phase. Hence, the phase relationship between the two blocks matched by the motion vector must be considered.

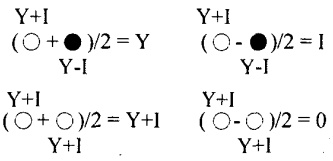

Fig. 10. Separation problem due to phase.

Fig. 11 shows the matching pattern according to the motion vector and clearly demonstrates that only the horizontal component of the motion vector affects the phase relationship. Meanwhile, an even horizontal vector reveals a reversed phase, and an even one shows an identical phase.

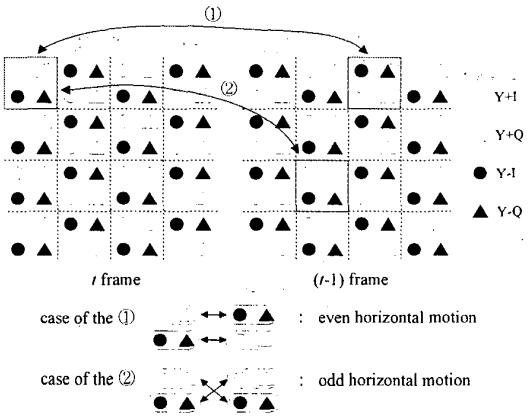

Fig. 11. Motion compensation-based Y/C separation.

A block matched using a reverse phase separates the Y/C components by adding and subtracting the composite values. In the case of an identical phase, the upper line pixels in the reference block are added and then subtracted from the lower line pixels in the matched block. For the lower line pixels in the reference block, the same calculation is performed using the upper line pixels in the matched block. Since the pixels in a 2x2 block adjoin each other, the similarity of the signal value is reliable.

```
If (m_h%2 == 0)
  for (i = 0;i < 2;i++)
    for (j = 0; j < 2; j++){
      C[a+i][b+j] = (Comp_t[a+i][b+j] - Comp_{t-1}[a+m_v+i][b+m_h+j])/2;
      Y[a+i][b+j] = Comp_t[a+i][b+j] - C[a+i][b+j];}
else
  for (j = 0; j < 2; j++){
    C[a][b+j] = (Comp_t[a][b+j] - Comp_{t-1}[a+m_v+1][b+m_h+j])/2;
    C[a+1][b+j] = (Comp_t[a+1][b+j] - Comp_{t-1}[a+m_v][b+m_h+j])/2;
    Y[a][b+j] = Comp_t[a][b+j] - C[a][b+j];
    Y[a+1][b+j] = Comp_t[a+1][b+j] - C[a+1][b+j];}
```

Fig. 12. Pseudo code for motion compensation-based Y/C separation.

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Fig. 12 shows the pseudo code for the Y/C separation algorithm based on motion compensation. In the code below, (mv, mh) and (a, b) represent an estimated motion vector for the vertical and horizontal direction, and the position of the processing block, respectively.

3.5. Overall Signal Processing

For Y/C separation, the proposed algorithm applies a different method according to the attributes of each region. A still region is distinguished by the movement detection procedure and passes through a frame comb filter. A residual moving region is divided into two regions, a possible and an impossible region, to compensate the motion information. The possibility for compensation is determined by a reliability checking process during the motion estimation procedure.

For a block with a reliable motion vector, the proposed motion compensation-based separation is applied. In contrast, a block that includes movement with an unreliable motion vector passes through a 3-line comb filter that only considers spatial similarity.

The overall structure of the proposed algorithm is shown in Fig. 13. A composite signal as the input signal is separated by a frame comb filter and 3-line comb filter. The output from the frame comb filter (Y1 and C1) and 3-line comb filter (Y2 and C2) is the input of a signal selector, which then selects the overall output according to the attributes of each region. A moving region detector distinguishes whether or not the processing block includes movement using two luminance signal frames (Y2) as the input. The motion estimator estimates the motion vector for a moving region using a criterion that identifies the block with the minimum block difference in the luminance inputs (Y2), and then outputs the motion vector to a motion compensation-based separator and the reliability information to a signal selector. Based on the estimated motion vector, the motion compensation-based separator then outputs a luminance (Y3) and chrominance (C3) for those blocks with reliable movement, while the signal selector chooses the final output from among the signals received from the three-comb filter using movement and reliability information.

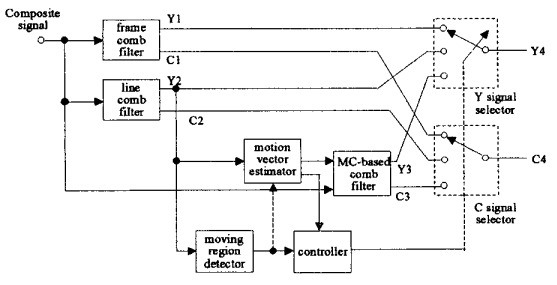


Fig. 13. Overall structure of proposed method.

4. EXPERIMENTAL RESULTS

In experiments, the resulting quality of the proposed method and a 3-line comb filter was compared. The test image, shown in Fig. 14, was 525x910 in size and consisted of a fluttering Stars and Stripes and static building with horizontal edges. The composite signal displayed in the gray level exhibited the phase inversion characteristic pixel-by-pixel. This feature of a composite signal means a Y/C separator can not apply a motion estimation algorithm to the process.

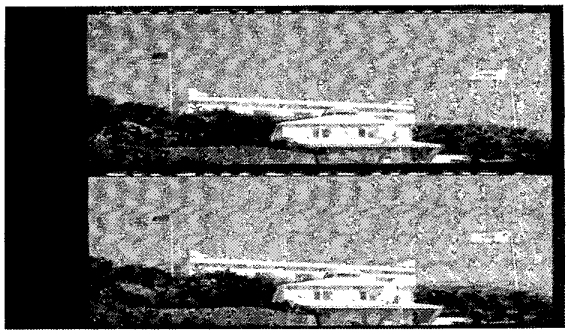
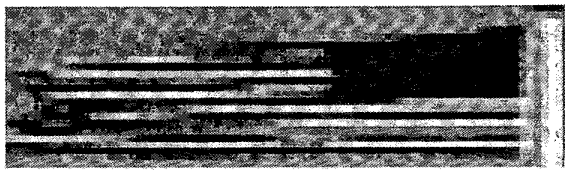
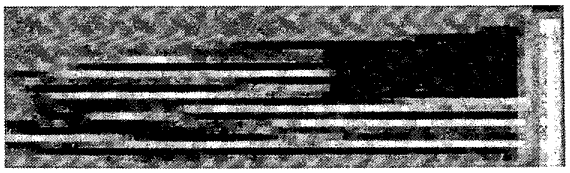


Fig. 14. Composite signal image displayed in gray level.



(a)



(b)

Fig. 15. Expanded resulting images for moving region. (a) 3-line comb filter. (b) proposed method.

Fig. 15 illustrates the expanded image of the decoded picture. Since this region had a large amount of movement, Figs. 15(a) and (b) simulated by a 3-line comb filter and the proposed method, respectively, show a different Y/C separation performance. Fig. 15(a) shows a rainbow pattern in the star section caused by cross coloring. In contrast, Fig. 15(b) includes no rainbow pattern or hanging dots, but shows a good recovery of the star pattern. Fig. 16 illustrates the

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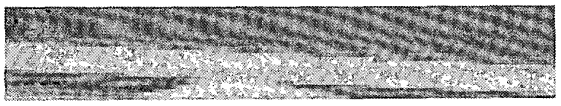
expanded result for the horizontal edge, which did not maintain a signal similarity along the vertical direction. Fig. 16(a), from the 3-line comb filter, includes cross luminance artifacts along the edge.



(a)

(b)

Fig. 16. Expanded resulting images for horizontal edge. (a) 3-line comb filter. (b) proposed method.

However, Fig. 16(b), from proposed method, has clear edges as a result of the frame comb filtering performed on this still region. Fig. 17 illustrates the overall structure of the hardware implementation and Fig. 18 shows the resulting waveform of a VHDL simulation. The experimental results confirmed that the proposed method was superior to conventional methods, especially for moving regions and horizontal still edges.

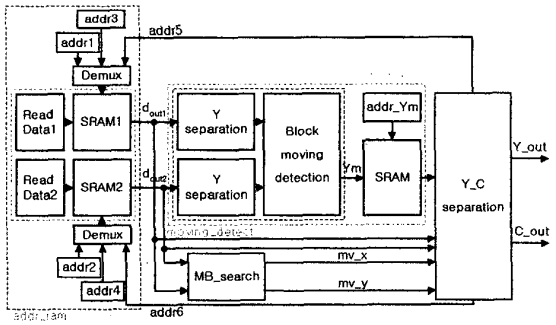


Fig. 17. Block diagram of hardware implementation.

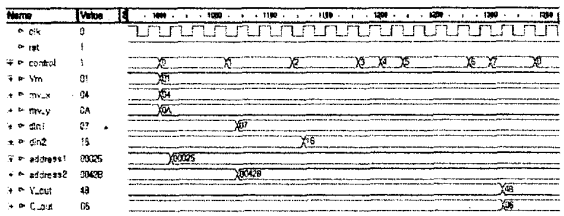


Fig. 18. Resulting waveform of VHDL simulation.

V. CONCLUSIONS

This paper presented an advanced Y/C separation algorithm for recovering a high quality NTSC picture. Cross color and cross luminance in moving regions still occur in conventional methods, however, in the proposed method, these problems are reduced through motion estimation. To apply the motion estimation algorithm, the features of a composite signal were analyzed and it was found that the chrominance component has a phase that inverts with a regular pattern. As such, a 2x2 block size was determined for the operation of the proposed method.. Consequently, for a moving region, the proposed method exhibited a better performance with a substantially reduced error based on compensating the motion and considering the phase.

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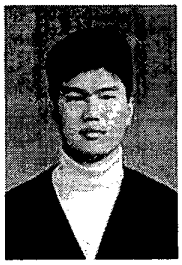

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